Original References are in italic and with serifs.
Answers are without serifs.

Response to Anonymous Referee #1

We thank the reviewer for her/his valuable comments. We respond to all comments and modified the paper accordingly.

The publication is an extensive comparison of different sensors to measure the integrated water vapor content (IWV) in the atmosphere and uses those results to evaluate two models, ICON and COSMO-DE, in order to assess if they reproduce the variability in the IWV.

After a detailed comparison of the instruments and the models, including discussion of temporal and spacial matching, the authors proceed to investigate the representativness of the data. The authors discuss one day as an example of the variation of the water vapor content.

The strengths and limitations of the used sensors are discussed and examples of the effect of the filtering due to the limitations of some sensors are given. Most notable are the change of the distribution of the values of IWV and the significant change of the mean diurnal variation of IWV if only measurements during clear sky conditions are used.

Given the importance and problems of measurements of water vapor I consider this study important and worth to be published after the comments raised below are taken into account. The publication is well written.

General remarks:

RC1: *Nothing about the sensitivity of the instruments in different altitudes has been said. Other instruments also measuring total columns, i.e. FTIR instruments in the TCCON and NDACC networks, have been investigated in this respect (e.g. Ostler, 2014 and Sussmann, 2013) and an introduction of a daily variation due to an altitude depending sensitivity has been found. The altitude depending variability has been traced back to the changing solar zenith angle and the different path of view. This is probably also true for the sun photometer which employs a similar viewing geometry like the FTIR instruments with a changing view path. Such an effect might (partially) explain the differences in the diurnal course of the instruments as shown in figure 2.*

AR1: Indeed, measuring with the sunphotometer at low solar zenith angles in combination with high IWV values, which are more likely at low altitudes, could lead to transmission approaching 0 (Ingold et al., 2000). We added this to the instrument description. Furthermore, we mention the variation due to the changing path through the atmosphere in p. 22853, l. 3 and go more into detail in p. 22861 l. 26: “For the difference between the sunphotometer and MWR, a dependency on the position of the sun is found (not shown). In the morning and in the afternoon, IWV from the sunphotometer is smaller than from the MWR because here the sunphotometer measures under lower elevation angles. At noon it is the other way around.

This could be due to an inaccurate relative air mass (Eq. 1) used by the retrieval or saturation effects due to low elevation angles.”

RC2: *Why are BASIL measurements are not used to derive an IWV? Why are the BASIL measurements not compared to a radiosonde profile? This would be advisable, because BASIL measurements are used to explain the properties of the water vapor column, i.e. that it concentrates in the first 1.5 km. I understand the correlation becomes very low if the distance becomes higher, even small distances introduce a comparison error for the IWV, as the authors explain in their study. But is this also true for the free tropopshere?*

AR2: BASIL is alone not able to measure the IWV because it can only provide profiles from a height of 50-180 m above ground up to a height of 3-8 km. To derive IWV the BASIL measurements must be combined with measurement from other instruments, for example microwave radiometer or tower measurements. However, these IWV measurements would not be independent. To make this more clear in the text, we added: “Due to its limited altitude coverage no column water vapor can be provided from BASIL measurements alone.” Since the study focuses on IWV, the profiles are not compared.

RC3: *I think the title does not quite reflect the content of the study. In my view it is an elaborate comparison of several instruments measuring the total water vapor content of the atmosphere. In order to do this in high quality the variability of water vapor both temporal and spacial has to be taken into account. Examples that the water vapor content can vary quickly both temporally and spatially have been given elsewhere and are not new.*

AR3: It is true that a large part of the study deals with the comparison of the numerous instruments. However, the instrument comparison serves the investigation of the IWV variability and not the other way around. Within this study we characterize the variability of IWV for different temporal and spatial scales and estimate the ability of different measurements to represent this variabilities and show e. g. that the microwave radiometer is the only instrument to capture the water vapour variability on time scales of a few minutes. Furthermore, the small scale variability is for the first time assessed with 156 m resolution runs by the new numerical weather forecast model ICON. As ICON will become operational in the next years we find it highly important to investigate how water vapor varies on these scales and whether the model is capable of resolving it.

Specific:

RC4: *Section 4.3 and Figure 9: Would COCMO-DE perform better if it would also be filtered for cloud-free conditions only, i.e. if only coincident values with the sun-photometer are taken into account.*

AR4: Since COSMO-DE does not have the same cloudy cases as the measurements at JOYCE filtering with the sunphotometer does not necessarily lead to clear-sky-only cases in the COSMO-DE output.

RC5: *In the summary, measurements of BASIL are not excluded from the statement, that all instruments compare well to each other. However, no IWV has been derived from BASIL measurements, the authors do even state so without giving a reason why it is not done. Either BASIL measurements should be included in the comparison of IWV or it should be made clear, that BASIL measurements have not been compared to other measurements.*

AR5: See answer to RC2. We modified the text to make this clear: "Pairwise comparison of the IWV-measuring instruments with 15 min temporal resolution..."

RC6: *Page 22864, line 15: I am not sure if the auto-correlation can be 'lost'. This statement seems a bit off-hand and should be more precise, especially if the information is there. The criterion of 1/e for not being correlated anymore seems quite arbitrary. If there are studies which justify this value, please cite them. Otherwise I would suggest removing or modifying the statement that the correlation is 'lost'.*

AR6: We modified the sentence to: "Synoptic influence is mainly responsible for the fact that the e-folding time of the auto-correlation is approximately one half of a day."

Minor:

RC7: *Page 22863, line 13: The statement that the '...high end tail of the distribution...disappears ...' is somewhat unclear. I needed some searching before I could match it to section 4.2. where this is investigated. I would recommend to change this to something like: 'the high IWV values are only measured during clear weather conditions on daytime' or similar.*

AR7: We modified this to: "Secondly, clouds and broken cloud fields can cause standard deviations of IWV of over 1.5 kg m^-2 within time intervals of a few hours. These high standard deviations do not occur when only daytime clear-sky IWV estimates are considered (cf. Fig. 8)."

RC8: *Figure 2, middle panel: The MODIS values are hard to see, because there are so few of them. I would suggest drawing them with a different, bigger symbol are increase their visibility.*

AR8: The figure is modified accordingly (see Fig. 1 in the discussion).

RC9: *Figure 3, lower panel: GPS and ICON colors are very similar, I had to look twice to be able to distinguish them*

AR9: The figure is modified accordingly (see Fig. 1 in the discussion).

RC10: *Figure 4: Please encircle the dots with a frame. Especially on the left plot their are to similar to the ICON values to be easily distinguished.*

AR10: The figure is modified accordingly (see Fig. 2 in the discussion).

RC11: *Figure 6: while I quite like this figure quite it is rather small. I would suggest to scale this figure at least to fill the page width.*

AR11: This is due to the layout of ACPD articles. In the final layout of ACP it will be larger.

RC12: *Figure 8: I am not sure if I understand this figure right. I would expect 4 different bars indicating the 10, 25, 75 and 90 percentiles. However I only see two of them.*

AR12: The lower and upper end of the thin bar indicates the 10%- and 90%-percentiles, respectively and the lower and upper end of the thick bar indicates the 25%- and 75%-percentiles, respectively.

RC13: *Figure 9: The shaded green area is barely visible on my print out. I would suggest to put a dashed line as a frame around it.*

AR13: The figure is modified accordingly (see Fig. 3 in the discussion).

References:

Ingold, T., Schmid, B., Mätzler, C., Demoulin, P., Kämpfer, N., Modeled and empirical approaches for retrieving columnar water vapor from solar transmittance measurements in the 0.72, 0.82, and 0.94 μm absorption bands, J. Geophys. Res., 105, 24327-24343, 2000.

Multi-station intercomparison of column-averaged methane from NDACC and TCCON: Impact of dynamical variability A. Ostler, R. Sussmann, M. Rettinger, N. M. Deutscher, S. Dohe, F. Hase, N. Jones, M. Palm, and B.-M. Sinnhuber Atmos. Meas. Tech. Discuss., 7, 6743-6790, 2014

First intercalibration of column-averaged methane from the Total Carbon Column Observing Network and the Network for the Detection of Atmospheric Composition Change R. Sussmann, A. Ostler, F. Forster, M. Rettinger, N. M. Deutscher, D. W. T. Griffith, J. W. Hannigan, N. Jones, and P. K. Patra Atmos. Meas. Tech., 6, 397-418, 2013

Response to Anonymous Referee #2

We thank the reviewer for her/his valuable comments. We respond to all comments and modified the paper accordingly.

Most of my comments were properly addressed by the authors during the previous rewiev. The article presents the interesting results of a multi-instrument campaign with focus on short-term variability. Since the spatio-temporal variability of water vapour is not well known and measured yet, I recommend a publication in ACP.

RC1: *I only see one point for improvement. The theory and the past research works about small-scale variability of water vapor are not well described in the ACPD article. Thus a reader can loose the orientation inside the article when the basic principles of IWV variability are not explained. As a consequence the reader don't get a comprehensive picture and may not see your research strategy or a need for high-resolution measurement campaigns. It might be good to tackle this problem by starting from theoretical considerations, e.g., which atmospheric processes can induce a fast change of IWV over a small horizontal distance? Possibly you come to the sensitivity of IWV to convection cells. Generally it will be helpful for your research and for the readers if you add an half page about the theory and past works. In this context a recent PhD thesis by L. Fischer might be useful too:*
http://edoc.ub.uni-muenchen.de/16208/1/Fischer_Lucas.pdf
L. Fischer, Statistical Characterisation of Water Vapour Variability in the Troposphere, Thesis , 2013
There were multi-instrument campaigns such as COPS and HyMex which are not mentioned yet.

AR1: We modified the beginning of the introduction to: "Water vapour is not only the most effective greenhouse gas (Kiehl et al., 1997) but also an important part of the hydrological cycle, so that the exact knowledge on atmospheric moisture is absolutely essential for both numerical weather prediction (NWP; e. g., Weckwerth et al., 1999) and climate modeling (e. g. Bony et al., 2006). Due to its importance water vapour has been investigated in several field campaigns such as HYMEX (Drobinskie et al., 2014) and COPS (Wulfmeyer et al., 2011). However, there is still need for research about its role in various atmospheric processes. The interaction between atmospheric humidity and convection, for example, is still poorly understood (Sherwood et al., 2010).

The amount of water vapour in the atmosphere is influenced by both mixing and transport as well as sources and sinks, such as condensation and evaporation of clouds and precipitation and evaporation of soil moisture. The subsequent vertical transport of the atmospheric water vapour occurs by turbulent mixing on small-scales (1 min and 10 m). Convective processes on different scales, such as meso-scale up- and downdrafts, and eddies at convective (10-30 min, < 2 km) and smaller scales, dominate the further vertical transport of water vapour. A prominent example of the convective scale is the atmospheric boundary layer where evaporation from the heterogeneous land surface and turbulent mixing create strong water vapour variability (Shao et al., 2013, cf. Fig. 10). Additional to these circulations, on large-scales (> 1000 km, > 1 day) water vapour is transported by advection of air masses. The combination of these various processes results in a high variability of atmospheric water vapour in both space and time.”

RC2: *To some extent the statistical methods of the present article could be improved and the model data could be analyzed on a higher level (e.g. derivation of vertical water vapour flux). However this could be also realized in a follow-on-study.*

AR2: We agree that the analysis could go further. However, we think this is beyond the scope of this study.

Minor remarks:

RC3: *abstract: line 9 "a good agreement in terms of standard deviation" do you mean the standard deviation of the diffences between coincident measurements of two instruments? I am asking since later standard deviation is used to characterize the temporal variability of water vapour. actually one has to characterise the mean differences and their uncertainties*

AR3: We modified the sentence to: “The statistical intercomparison of the unique set of observations during HOPE (microwave radiometer (MWR), Global Positioning System (GPS), sunphotometer, radiosondes, Raman Lidar, infrared and near infrared Moderate Resolution Imaging Spectroradiometer (MODIS) on the satellites Aqua and Terra) measuring close together reveals a good agreement in terms of random differences (standard deviation <=1 kgm^-2) and correlation coefficient (>= 0.98).”

RC4: *p.22839, line 6 "However, the interaction between atmospheric humidity and convection..." How about the temporal and spatial scales of convection? What happens to IWV in convection cells? I think there are studies which can provide the reader with numbers, e.g. convection time scales: 10-30 min , horizontal scales < 2 km. It is your task to give such infos to the reader within the introduction.*

AR4: We agree that this is an important information. Therefore we included this in the introduction as you can see in the answer to RC1.

RC5: *section 2.1.4 how is the vertical resolution of the Raman lidar?*

AR5: The resolution of BASIL is mentioned at page 22845 in line 18: “...water vapour profiles with a vertical resolution of 30 m are provided every 5 min...“

RC6: *p. 22851,line 28 what is a residual layer? I don’t see the layer in Fig. 2p.22860*

AR6: The turbulence in the planetary boundary layer decreases shortly before sunset. This formerly well-mixed layer is called residual layer.

It often exists until the morning when the mixing layer starts to form again (e. g. Stull, 1988). We added this reference to the paper.

RC7: *"... the importance of the IWV variabilty associated with atmospheric turbulence." did you really show this? I have more the picture that IWV can suddenly increase if an updraft region moves through the MWR line of sight. That's not turbulence but convection. In your conclusions it is the second forcing (cloud, cell) which is larger than the third forcing (turbulence) of IWV variability.*

AR7: We modified the sentence to: "The previous sections show the importance of the IWV variabilty associated with atmospheric turbulence and convection".

RC8: *For interpretation of the daily cycle of atmospheric water:*
Linda Schlemmer, Cathy Hohenegger, Jürg Schmidli, Christopher S. Bretherton, and Christoph Schär, 2011: An Idealized Cloud-Resolving Framework for the Study of Midlatitude Diurnal Convection over Land. J. Atmos. Sci., 68, 1041–1057. doi: http://dx.doi.org/10.1175/2010JAS3640.1

AR8: We thank the reviewer for this helpful reference. We modified a paragraph of Sect. 4.3 to: "Interestingly, the spread between the different ensemble members is highest around the time of maximum IWV (~ 17:00 UTC). Since there is interaction between humidity, time and strength of convection and resulting precipitation (Schlemmer et al. 2011) this might be associated with difficulties of the forecast model with convective precipitation."

Comments from previous review:

RC9: *I am not a native English speaker, however, some sentences could be optimized and the paper would become clearer. Intercomparison studies can be very complex as in your case. Thus I would recommend to make item lists (or bullets) for agreements, disagreements, important characteristcs. That's easier for understanding, for the memory and for possible future consultations of your article.*

AR9: We modified a part of the summary to:
"The multi-instrument intercomparison reveals a number of aspects for the individual instruments:
- Sunphotometer measurements show a good agreement with the other measurements but can only be conducted during clear-sky at daytime and seem to suffer from problems when the sun is low.
- IWV from MWR and GPS differs only slightly (bias: 0.2kgm^-2 (1%), standard deviation: 0.9kgm^-2 (6%), cf. Fig. 6) taking the specified instrument uncertainties into account.
- Near-real time processed GPS data exhibit inconsistencies at the beginning of each day and each hour due to the processing procedure that might also lead to a shift in the diurnal cycle of IWV. Further work on the processing might increase the performance of the GPS measurements.
Despite the characteristics of the measurements themselves other aspects

have to be taken into account to judge the instruments. For example, a comprehensive GPS networks exist, thus making GPS better suited to evaluate models over their whole domain.
The analysis of the temporal variability of IWV reveals three distinct sources.
- Synoptic influence is mainly responsible for the fact that the e-folding time of the auto-correlation is approximately half a day.
- Clouds and broken cloud fields can cause standard deviations of IWV of over 1.5kgm^-2 within time intervals of a few hours.
- Atmospheric turbulence determines IWV variability also in cloud-free conditions on scales below 1 h.
The high standard deviations during cloudy time periods do not occur when only daytime clear-sky IWV estimates are considered (cf. Fig. 8). Therefore, instrument intercomparisons under cloud free conditions are advantageous to assure more homogeneous conditions. The high resolution (a few seconds) of the MWR enables to observe standard deviations higher than 0.5kgm^-2 for time intervals less than 30 min. This information is interesting for the development of sub-grid parameterizations for atmospheric models but also implies that instrument intercomparisons should make use of suitable measures to identify atmospheric conditions with low variability in order to isolate instrument errors."

RC10: *line 394 what are height-based levels? Same as terrain-following coordinates of COSMO?*
Please provide a clear description

AR10: Yes, the ICON height levels are terrain-following levels as in COSMO-DE. We changed the description of ICON to make this clearer: "50 generalized terrain-following levels are used in the vertical..."

RC11: *line 202*
The GPS signal consists of electromagnetic waves with frequencies of …
The main effect of the neutral atmosphere is to decrease the propagation speed of the GPS signal ?

AR11: That is true. To make this clearer we modified the text to: **"**The remaining part of the delay is due to the neutral, moist atmosphere, which refracts incoming electromagnetic waves, increasing the travel time of GPS signals (Solheim, 1999)."

References

Drobinski, P., Ducrocq, V., Alpert, P., Anagnostou, E., Béranger, K., Borga, M., Braud, I., Chanzy, A., Davolio, S., Delrieu, G., Estournel, C. Filali Boubrahmi, N., Font, J., Grubišić, V., Gualdi, S., Homar, V., Ivančan-Picek, B., Kottmeier, C., Kotroni, V., Lagouvardos, K., Lionello, P., Llasat, M. C., Ludwig, W., Lutoff, C., Mariotti, A., Richard, E., Romero, R., Rotunno, R., Roussot, O., Ruin, I., Somot, S., Taupier-Letage, I., Tintore, J., Uijlenhoet, R., Wernli, H., HyMeX: A 10-Year

Multidisciplinary Program on the Mediterranean Water Cycle, Bull. Amer. Meteor. Soc., 95, 1063–1082, 2014.

Solheim, F. S., R. Vivekanandan, R. H. Ware, and C. Rocken, Propagation Delays Induced in GPS Signals by Dry Air, Water Vapor, Hydrometeors and other Atmospheric Particulates, Journal of Geophysical Research, 104, 9663-9670, 1999.

Stull, Roland: An Introduction to Boundary Layer Meteorology, Kluwer Academic Publishers, 1988.

Wulfmeyer, V., Behrendt, A., Kottmeier, C., Corsmeier, U., Barthlott, C., Craig, G. C., Hagen, M., Althausen, D., Aoshima, F., Arpagaus, M., Bauer, H.-S., Bennett, L., Blyth, A., Brandau, C., Champollion, C., Crewell, S., Dick, G., Di Girolamo, P., Dorninger, M., Dufournet, Y., Eigenmann, R., Engelmann, R., Flamant, C., Foken, T., Gorgas, T., Grzeschik, M., Handwerker, J., Hauck, C., Höller, H., Junkermann, W., Kalthoff, N., Kiemle, C., Klink, S., König, M., Krauss, L., Long, C. N., Madonna, F., Mobbs, S., Neininger, B., Pal, S., Peters, G., Pigeon, G., Richard, E., Rotach, M. W., Russchenberg, H., Schwitalla, T., Smith, V., Steinacker, R., Trentmann, J., Turner, D. D., van Baelen, J., Vogt, S., Volkert, H., Weckwerth, T., Wernli, H., Wieser, A., Wirth, M., The Convective and Orographically-induced Precipitation Study (COPS): The scientific strategy, the field phase, and research highlights, Q. J. R. Meteorol. Soc., 137, 3 – 30, DOI:10.1002/qj.752, 2011.